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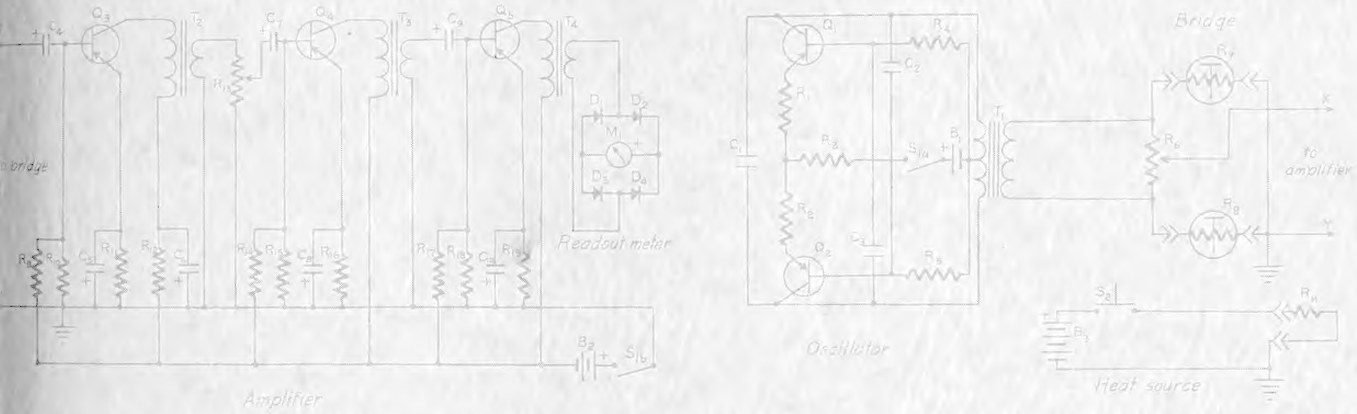

ROCKY MOUNTAIN FOREST AND RANGE EXPERIMENT STATION
RAYMOND PRICE, DIRECTOR FORT COLLINS, COLORADO
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AN INSTRUMENT FOR DETECTING SAP MOVEMENT IN WOODY PLANTS

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Robert H. Swanson, Research Forester

Rocky Mountain Forest and Range Experiment Station[1]

[1] Central headquarters maintained in cooperation with Colorado State University at Fort Collins.

C O N T E N T S

AN INSTRUMENT FOR DETECTING SAP MOVEMENT IN WOODY PLANTS

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What really happens inside a tree? When does it transpire? Does one species use more water than another? Does sap move during periods of drought, darkness, light, extremes of cold or heat? These are questions that foresters and others have been asking for years.

One possible way to answer some of these questions is to measure the rate of sap movement. The rate can be determined partly by the heat transport method, that is, by timing the rate of movement of a heat pulse from one point to another in a plant, and partly by calculation. As far as is known, no one has described a portable instrument for detecting sap movements by this method.

This paper describes such an instrument--a timer so to speak--that enables one to obtain data for solving an equation relating time and heat-pulse velocity. The instrument can be used on any stem, branch, or root larger than one-half inch in diameter.

The use of the heat transport method to detect sap movement is not an original idea. Huber and Schmidt (1937) demonstrated that heat transport was an index of sap movement. Marshall (1958) elaborated on their work and proved mathematically and experimentally that the rate of sap movement was measurable if diffusion of heat through the combined sap and wood, as well as sap movement, were taken into account. He derived equations for obtaining both diffusivity and heat-pulse velocity from measurements of distance and time-temperature ratios. Another worker, Closs (1958) derived an equation that involved the measurement of time and distance alone. Both Marshall and Closs demonstrated that the heat-pulse velocity is related to sap flux.[2] Neither described in detail the instrumentation required to measure heat-pulse velocity.

WHAT IS IT?

The sap movement detector is an instrument that can be used to measure the velocity of a heat-pulse in a sap stream of a woody plant (fig. 1). With it any heat-pulse velocity of 0.3 cm./hour or greater can be measured. When the speed is less, the presence or absence of movement can be detected, but not the speed.

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[2] Sap flux is defined as the number of cc. of sap crossing each sq. cm. of sapwood perpendicular to the direction of flow in a unit time.

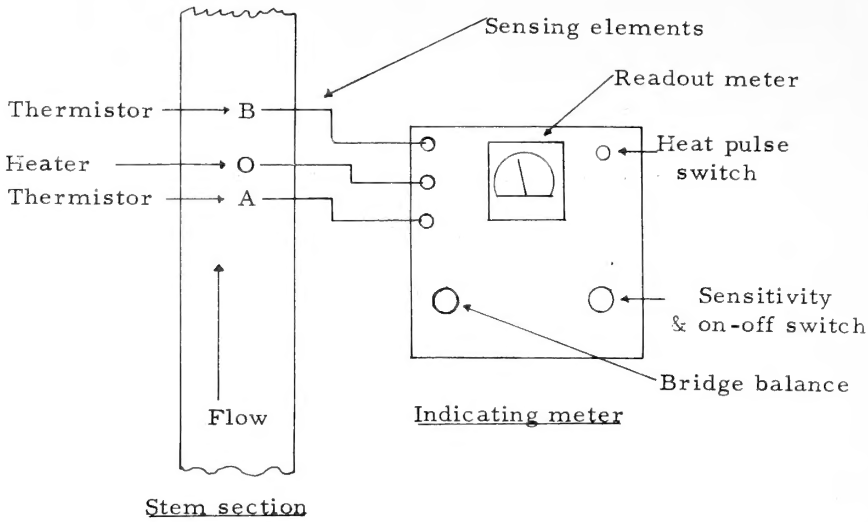

Figure 1. --Block diagram of a sap movement detector.

It is a lightweight, portable instrument. Five transistors and two thermistors are used in a compact, battery-operated circuit. The total weight, including all accessories, is less than 10 pounds. Its size is 6 by 9 by 5 inches. One man can easily carry and use this instrument.

The instrument consists of three basic parts: sensing elements, indicating meter, and timer. The sensing elements are three hypodermic needles. Two of these are miniature thermometers. These each consist of a needle with a thermistor (a device which changes in resistance with changes in temperature) embedded in the tip. The third sensing element is a heat source, a tiny electric "stove." It, too, consists of a hypodermic needle, but with a heater wire enclosed, rather than a thermistor.

The indicating meter is the main housing. The timer is a stopwatch. Other accessories used are a drill jig, drill bits, and drill.

USES FOR THE INSTRUMENT

Heat-pulse velocity measurements are useful in themselves. They are an index to sap movement. Velocity implies both speed and direction of movement. Such information should indicate when a tree is transpiring, when movement from or into storage is taking place, the portion of a stem having the greatest amount of movement, which branches are transpiring most, which roots are supplying the most water, etc.

It may possibly be used to determine absolute transpiration rates. To obtain information relating to actual quantities moved, or volume rates of flow, both sap velocity and conducting area must be known. This use is dealt with in the section on theory. Suffice it to say, this instrument measures only heat-pulse velocity.

All of the above measurements involve problems such as where to sample, how deep to sample, how many samples to take, and the unknown effect of inserting the probes. These limitations have not been fully explored; hence, users will have to work out some of their own refinements.

ACCURACY OF THE MEASUREMENTS

It is necessary here to point out that validity of a theory, and accuracy of an instrument with regard to the measurement of variables are two entirely different subjects. Proof of the validity of heat-transport theory is beyond the scope of this paper. The present discussion relates to the instrument alone.

Three variables: distance, time (t), and temperature difference are either measured or established with the sap movement detector. The distances between the heat source and the thermistor probes are the most important of these variables. Precision drilling in the construction of the drill jigs is a necessity. The error in the distance between holes in the jig can be held to $\pm$ 0.001 cm. without difficulty. However, holes drilled into a stem with the aid of a drill jig will not reflect this degree of precision. A figure for the accuracy of these holes is $\pm$ 0.01 cm. This means that for a velocity of 5 cm./hour, (spacing difference = 0.5 cm. $\pm$ 0.01 cm.; t = 180 seconds), the error in spacing can influence the reading by $\pm$ 0.1 cm./hour.

Time can be measured with any degree of precision. The stopwatch intended for use with this instrument is accurate to $\pm$ 0.5 second. At a heat-pulse velocity of 5 cm./hour as in the above example, an error of 0.5 second could cause an error in the reading of $\pm$ 0.01 cm./hour, a relatively insignificant figure.

Temperature difference is measured with this instrument to a precision of $\pm$ 0.0125° C. This means that zero temperature difference can be read within 0.025° C. An error of this small magnitude would probably be masked by unpredictable changes in the ambient temperature of a plant. I don't consider it a significant source of error.

HOW TO USE THE INSTRUMENT

Figure 2 illustrates the field use of the sap movement detector. This is a prototype model with two meters. Later models use only one meter. However, the principle of operation is the same.

To obtain a heat-pulse velocity reading, the user must first select a stem, root, or branch and with the aid of the drill jig, drill three small holes. Next the probes are inserted, connected to the indicating meter, the meter turned on and balanced to indicate zero temperature difference between the two thermistor probes. Then the heat pulse switch is depressed for 1 second, and the stopwatch is actuated. When the readout meter returns to zero, the stopwatch is stopped and the time elapsed noted. If the probes are spaced, relative to the heater probe, 0.5 cm. below, and 1.0 cm. above, then

$$V = \frac{900}{t_o} \quad \text{cm/hour}$$

In the above example, if the time noted were 300 seconds, then V = 900/300 or 3 cm./hour. The average time required to set up the instrument and take one velocity reading is 10 minutes.

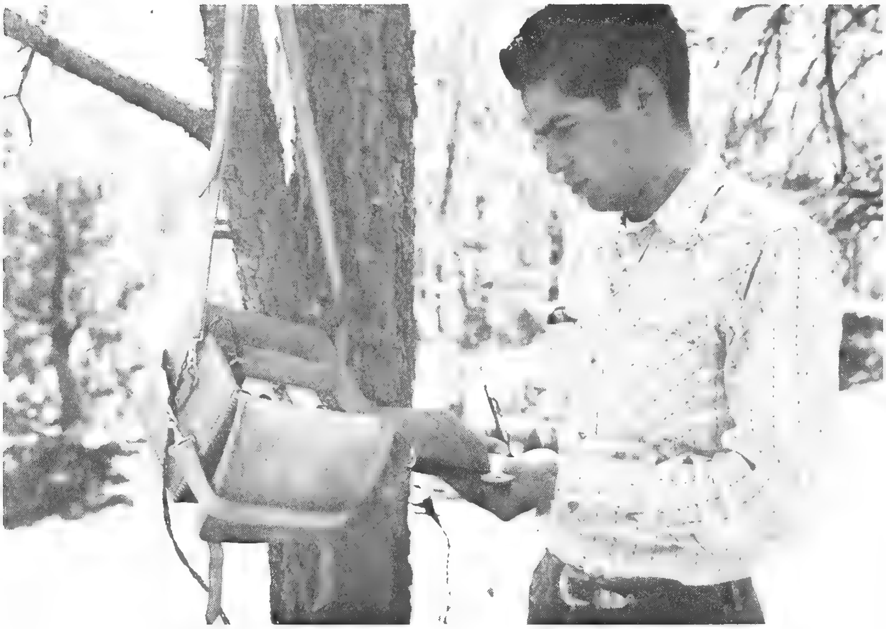

Figure 2.--Using the sap-movement detector on a small ponderosa pine. The probes (sensing elements) are directly below the observer's left hand.

HOW DOES IT WORK?

This instrument allows one to determine the effect of sap movement on heat-pulse velocity. As illustrated in figure 3, heat is applied at point O. At point B, the rate of heat rise with time is measured. The distance OB divided by the time required for maximum heat at B is velocity. However, this velocity is not that of the moving sap alone, but is a resultant of the rate of heat diffusion through the wood tissues, and the velocity of the heat pulse moving with the sap stream.

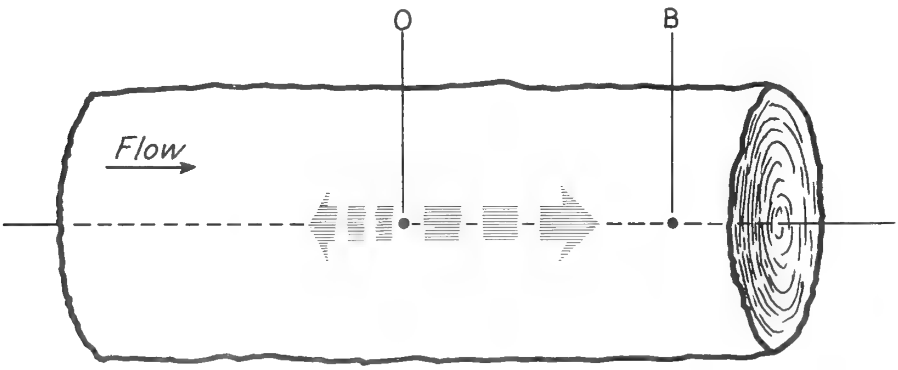

Figure 3.--Stem section with sap flow.

Figure 3 is an ideal model where the heat pulse is both injected and measured on the flow axis so that lateral components of heat diffusion can be ignored.[3] The rate of heat from O to B without sap flow for this model is defined by equation (1), (Marshall, 1958).

$$T_B = \frac{Q}{4\,\pi\,Kt}\ \exp - \frac{(O\ B)^2}{4Kt} \qquad {}^\circ C. \qquad (1)$$

where T_B = Temperature at point B, °C

Q = Heat input

K = Thermal diffusivity of plant tissue, $cm.^2/sec.$

t = Time from start of heat input at O

OB = Distance in cm.

Heat-pulse velocity can be added to equation (1) as a distance (Vt). This is shown in equation (2).

$$T_B = \frac{Q}{4\,\pi\,Kt}\ \exp - \frac{(OB\ -\ Vt)^2}{4Kt} \qquad {}^\circ C. \qquad (2)$$

Now if distance OB, Q, K, and t are known, then T_B can be measured and equation (2) solved for V. However, these variables are hard to measure. Another method of obtaining V is to set up an equation for a second point T_A, and solve the two equations simultaneously. The condition described here is illustrated in figure 4.

The equation describing the temperature at A is:

$$T_A = \frac{Q}{4\,\pi\,Kt}\ \exp - \frac{(-OA-Vt)^2}{4Kt} \qquad {}^\circ C. \qquad (3)$$

A simultaneous solution of equations (2) and (3) for V at time t_o when $T_A = T_B$ yields:

$$V = \frac{OB\ -\ OA}{2\ t_o} \qquad cm./sec. \qquad (4)$$

or

$$V = \frac{1800(OB\ -\ OA)}{t_o} \qquad cm./hour \qquad (5)$$

Initially, the temperature at A equals that at B. A short time after heat is applied to O, the temperature at A begins to exceed that of B. At some later time, the temperature at B again equals that at A. The time from initial heat application until the temperature at A equals that at B is defined as t_o. Figure 5 is a raw data curve obtained with the meter. Distances OB and OA are predetermined distances, usually 1 and 1/2 cm., respectively. Time t_o is determined with a stopwatch and this instrument. Thus, heat-pulse velocity is obtained from equation (5).

[Note: In all cases, the distance OB, or the distance to the probe downstream from point O, must be greater than distance OA. This is true regardless of the probe's physical location on a tree. In other words, if the flow was from

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[3] All equations in this paper are written for the simplified model of figures 3 and 4. Marshall included these components in his equations.

leaf to root, instead of from root to leaf as illustrated in figure 1, the position of the probes would be reversed; probe A would be the upper probe, and B the lower. If, in the taking of a velocity reading, the direction of flow is assumed incorrectly, then this will be indicated by either erratic (jumpy) meter readings, a t_o reading of much greater magnitude than with the correct directional spacing, or both. If direction of flow is not definitely known, then two velocity readings, one in each direction, should be taken. The reading yielding the lowest t_o value is correct.]

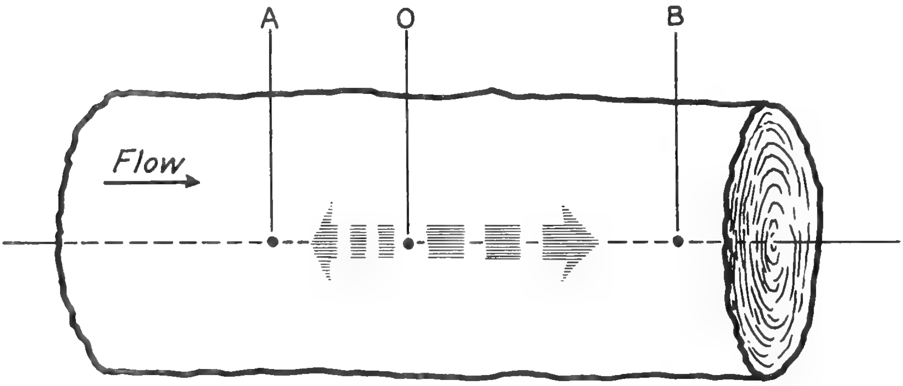

Figure 4. --Stem section with sap flow.

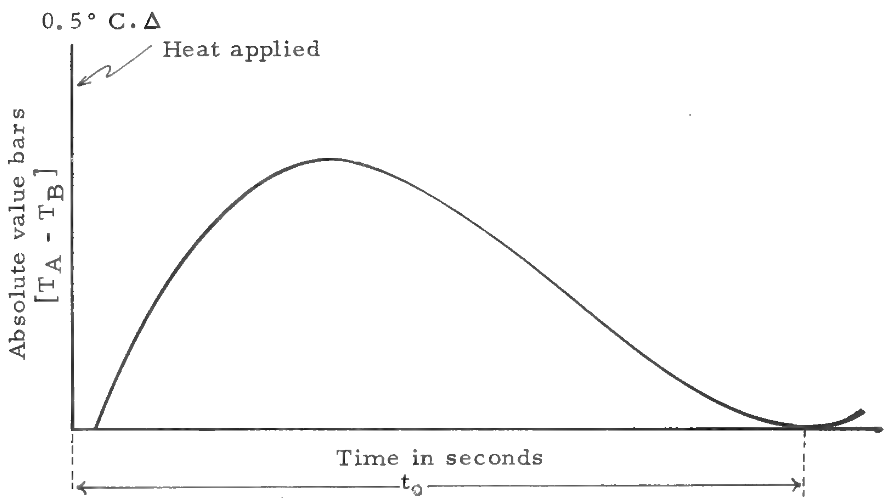

Figure 5. --Raw data curve, sap velocity meter.

In use, the sap-movement detector has at least one limitation. An examination of equation (5) reveals that V = O only if t_o is infinite or if (OB-OA) is zero. In practice, t_o cannot exceed 600 to 900 seconds. This is due to the fact that heat dissipates or is conducted from any body to the surrounding atmosphere as long as the temperature of its surroundings is lower than the temperature of the body.

Since this method involves heating only part of a body, it is logical to assume that in most, if not all cases, the body when heated will be warmer than its surroundings, and heat will be conducted out of the body.

A series of tests for time of heat dissipation in stems with known zero movement indicated that for a surrounding medium temperature of 25° C. the heat dissipation time was about 1800 seconds, and if the surrounding temperature was lowered to 0° C. the time was about 900 seconds. If this same trend continues below 0° C., a further reduction in heat dissipation time is indicated. A figure of 600 seconds appears to be fairly safe except when the ambient temperature is well below freezing.

With this limitation in mind, any reading of t_o greater than 600 seconds should be considered a possible error source, and velocity readings so obtained treated accordingly.

Now heat-pulse velocity is a function of both t_o and distance (OB-OA). This distance can be made as small as desired, even down to and including zero. For obtaining velocities in the field, it is impractical to set this distance at less than 0.1 cm. This value for (OB-OA) results in

$$V = \frac{180}{t_o} \quad \text{cm/hour} \tag{6}$$

Since t_o should not exceed 600 seconds, V obtained using equation (6), cannot be slower than 180/600 or 0.3cm./hour. Other distances of OA and OB can be used if a greater lower limit on velocity can be tolerated. An example of a suitable distance is OA = 0.5 cm., OB = 1.0 cm. This results in

$$V = \frac{900}{t_o} \quad \text{cm/hour} \tag{7}$$

and a lower limit of measurable velocity of 900/600 or 1.5 cm/hour.

In the second case (OB-OA=O), obviously t_o is irrelevant, and any value for $t_o > 0$ would still yield a value of $V = 0$. Thus, this spacing is not useful for measuring velocity. However, this spacing is useful for detecting the presence or absence of movement. Any reading on the readout meter with equal probe spacing indicates some movement. If this movement is faster than 0.3 cm./hour, then the sap movement detector can be used to measure it.

All of the above describes, in general, the theory and limitations of sap movement detection in an ideal model. The relationship expressed in all equations is mathematically exact for this model. If the assumption of an ideal model is acceptable, and the model can be carried over into the realm of actuality, then the velocity measured with this instrument is the heat-pulse velocity. Whether or not this assumption is valid is subject to question.

Vite and Rudinsky (1959) have shown that sap movement is spiral in certain conifers and vertical in others. If an inspection of a stem will reveal the plane of movement, then the sensing elements can be aligned in this plane so as to satisfy the conditions set for the model. If an inspection will not reveal this information, then some other means, such as taking a large number of samples in several planes, must be formulated to allow for the discrepancy between the model and the actual case. This is a problem for future study.

HEAT-PULSE VELOCITY VS. RATE OF SAP FLOW

The general validity of the theoretical analysis has been established above. Thus the problem remaining is to relate heat-pulse velocity to actual rate of sap flow.

$$V = au \frac{Ps \quad Cs}{PC} \tag{8}$$

where V = heat-pulse velocity

a = the fraction of any plane area perpendicular to the flow axis which is occupied by sap streams moving at a velocity parallel to this axis.

u = sap velocity

Ps = sap density = 1.00

Cs = specific heat of sap (water) = 1.00

P = density of green wood

C = specific heat of combined wood and sap

Equation (8) cannot be used to determine u because the fraction a is unknown. Also, there is some question as to whether sap velocity is the most useful term for comparison of one species against another. The alternative to sap velocity is to use sap flux, that is, the number of cc. of sap crossing each sq. cm. of sapwood perpendicular to the direction of flow in unit time. To quote Marshall (1958):

> "It appears that values for sap speeds may be used for two purposes, either to compare rates of sap flow at different times and different places (in the same or different trees), or to relate the sap flow to other numerical quantities such as the rate of evaporation from the leaves, or the moisture intake at the roots. For the first purpose the sap flux is just as useful a measure as the sap speed, and for the second, it is more useful because to relate the sap speed to quantities like the above (evaporation, moisture intake), the speed must first be multiplied by the unknown factor a. For these reasons, and because the relation between the heat-pulse velocity and the sap flux is easily expressed in terms of quantities familiar to the timber technologist, it was decided to use the sap flux as the measure of sap flow."

$$\text{Sap flux} = P\,(m + 0.33)\,V\ ^{cc}/\text{sq. cm./hour} \tag{9}$$

where P = ovendried weight of wood ÷ green volume (g/cc)

m = water content ÷ ovendried weight (decimal fraction)

0.33 = specific heat of wood

V = heat-pulse velocity (cm./hour)

This equation was verified by Marshall. Predicted flow rate quantities using (9) and actual measured quantities were the same within a few percent (experimental error).

The only additional measurements necessary to relate sap flux to heat-pulse velocity are P and m. Both of these can be obtained from a single increment core near the point of measurement.

REPEATABILITY OF VELOCITY READINGS

One test conducted during this study was to determine the repeatability of readings taken with the sap-movement detector.

A series of velocity readings taken in a 15 cm. diameter willow stem that was supplied with water under pressures varying from 10 lbs./in.^{2} to 60 lbs./in.^{2} by 10 lbs./in.^{2} intervals, showed that readings taken at each pressure interval were highly repeatable. For measured heat-pulse velocities of 0.6 cm./hour or greater, the deviation from the mean measured velocity was $\pm$ 0.5 cm./hour or less. Below 0.6 cm./hour, the deviation was $\pm$ 50 percent of the mean. These data are shown in the following tabulation. The mean in each case is an average of at least eight velocity readings.

Applied pressure (lbs/in^2)	Mean measured velocity (cm/hour)	Range of velocity readings (cm/hour)
10	0.45	0.29 - 0.75
20	.65	.62 - .69
30	1.33	1.20 - 1.54
40	2.10	1.82 - 2.62
50	2.24	1.83 - 2.73
60	3.64	3.36 - 4.03

INSTRUMENT CONSTRUCTION

The complete schematic diagram of the sap-movement detector is shown in figure 6. The indicating meter housing is a 4- by 5- by 6-inch, or larger, aluminum box. The oscillator and amplifier are assembled on a 1/16- by 3- by 5-inch perforated phenolic board. Sockets should be used with either the 2N104 or 2N109 transistors. 2N217 transistors have long leads and can be wired directly into the circuit. These circuits are conventional and little difficulty should be experienced in their construction.

The only precaution to observe is to mount transformers T2, T3, and T4 at right angles to each other, or at least 1 inch apart to prevent interaction of their fields. Transformer, T1, has two secondary taps in addition to the common lead. The 8-ohm tap should be cut short at the transformer. Only the 16-ohm and common lead are used. The color code furnished with each of the transformers by each manufacturer should be followed when wiring them into the circuit.

Resistors R7 and R8 are thermistor probes. These are assembled in hypodermic needles. Many gages and lengths of hypodermic needles are available. The user will have to decide which size needle is best suited to his purpose. About 20-gage needles are the smallest that can be easily handled.

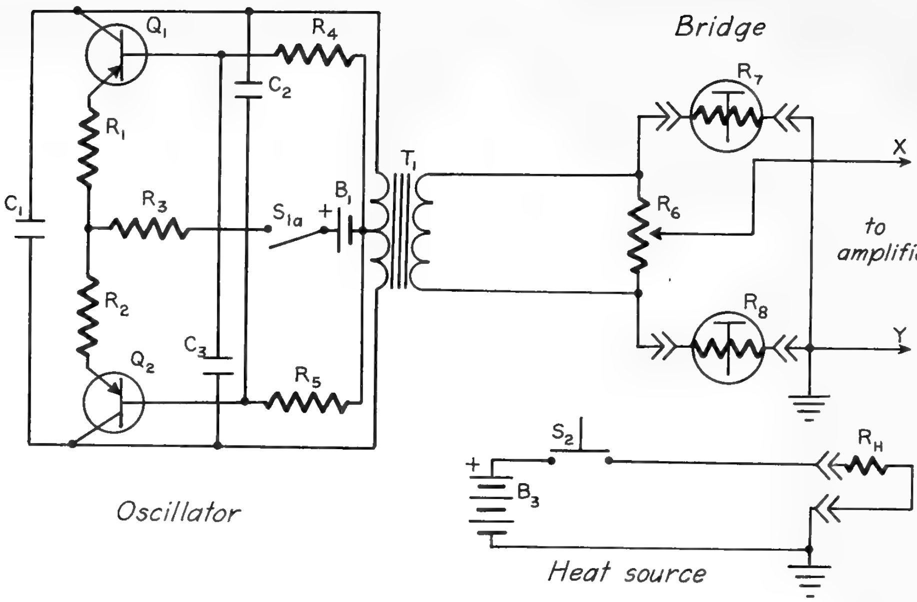

Figure 6A. --(Zarr, 1960). Circuit diagram: oscillator, bridge and heat source.

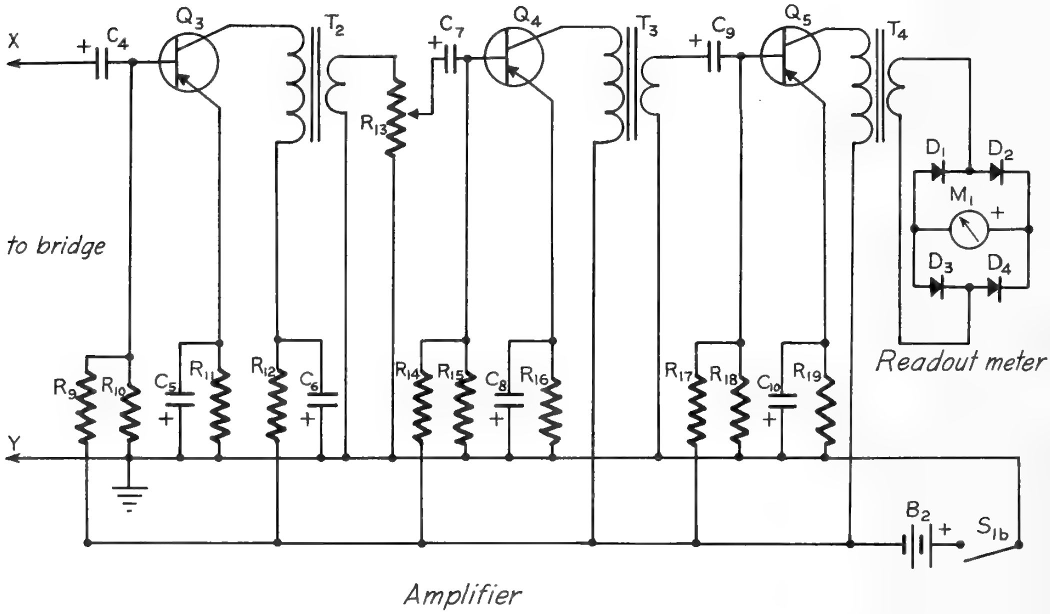

Figure 6B. --(Turner, 1960). Circuit diagram: amplifier and readout meter.

Parts List - Figure 6A and 6B

RESISTORS - (all resistors 1/2 watt carbon $\pm$ 5 percent, unless noted)

R1, R2	33 ohms
R3	240 ohms
R4, R5	100,000 ohms
R6	1,000 ohm 10 turn potentiometer (G. W. Borg Model 1111B or equivalent)
R7, R8	2,000 ohm at 25° C thermistors matched within 2 percent of each other (see text)
R9, R15, R18	2,200 ohms
R10, R14, R17	10,000 ohms
R11	100 ohms
R12, R16, R19	1,000 ohms
R13	100 ohm potentiometer with attached DPST switch S_{1a} and S_{1b}
R H	Heater (see text)

CAPACITORS:

C1	0.2 mfd paper
C2, C3	0.02 mfd ceramic disc
C4, C7, C9	10 mfd 6 VDC electrolytic
C5, C6, C8, C10	25 mfd 6 VDC electrolytic

DIODES:

D1, D2, D3, D4,	IN270 or equivalent

METER:

M1	0-50 microampere meter

TRANSFORMERS:

T1	Primary 48 ohms ct, secondary 8, 16 ohms, see text (Stancor TA-11 or equivalent)
T2, T3, T4	Primary 20,000 ohms secondary 1,200 ohms (UTC SO-7 or equivalent)

BATTERIES:

B1	1.5 volt penlight cell (Burgess type Z or equivalent)
B2	3 volt 2-penlight cells in series
B3	6 volt (Burgess type F4BP or equivalent)

SWITCHES:

S1a, S1b	DPST Switch mounted on R13
S2	Normally open momentary contact SPST toggle switch

TRANSISTORS:

Q1, Q2, Q3, Q4, Q5	2N104, 2N109, or 2N217 (see text)

PLUGS AND JACKS:

3 phono jacks - two for thermistor probes, 1 for heater lead
3 phono plugs - two for thermistor leads; 1 for heater probe
1 4-prong Jones plug and matching socket

For needles 18 gage or smaller, bead thermistors 0.014 inch diameter are used (Fenwall type GC32L1 or Veco 32A48). Bead thermistors 0.043 inch diameter can be used with needles 17gage and larger (Fenwall type GB32L1 or Veco 32A13). With any of these thermistors, a problem of short lead length must be faced. As supplied, the leads are 1 inch or shorter. One lead must be extended so that it is as long as the hypodermic needle with which it is to be used. These leads are platinum-irridium wire and cannot be soldered with rosin core solder. A stainless steel solder, All-State No. 430, is suitable.[4] The leads must be tinned with this solder, and all traces of the corrosive flux furnished with the solder removed with a weak base, such as bicarbonate of soda. The tip of the hypodermic needle must also be treated in this manner. Enameled copper wire extension leads are affixed to the thermistors. Thirty-six gage wire is used with the smaller beads; larger wire can be used with the others.

Another problem faced in assembling the thermistor probes is that of insulating the extended lead from the needle barrel. Insulating varnish or enamel was not suitable because it cooked off during the assembly soldering processes. Teflon tubing size 32 or smaller available from electronic supply houses is a suitable insulator.

When the techniques involved in lengthening the thermistor leads are mastered, assembly of the thermistor probes presents little difficulty. It is reduced to a series of steps as outlined below. Reference to figure 7 will help to clarify the steps.

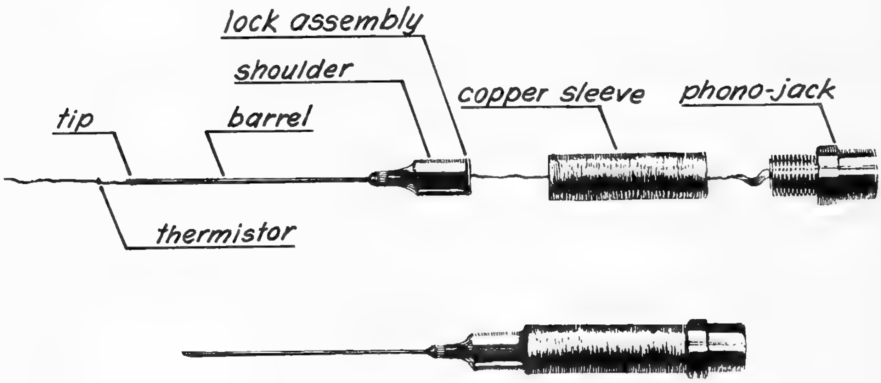

Figure 7.--Thermistor probe assembly, blown-up illustration with finished probe below.

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[4] All-State No. 430 solder is available at most welding supply houses in a 1 ounce sample kit for $1.00. This amount is sufficient for several dozen probes.

Thermistor probe assembly steps.

1. Tin thermistor leads with All-State No. 430 solder.

2. Solder desired length extension wire to thermistor lead. Use All-State No. 430.

3. Tin tip of hypodermic needle with All-State No. 430 solder. Clean off flux traces from needle and from extended lead.

4. Remove lock assembly and chrome plating down to shoulder of needle with a file.

5. Slip a 3/4 inch long by 1/4 inch I. D. copper sleeve over the needle and solder with rosin core solder to the needle shoulder.

6. Insert lengthened thermistor lead and teflon tubing into needle from tip end. Put a small amount of silicon temperature-conducting jelly around the thermistor before inserting it entirely into the barrel. The thermistor should be positioned 1/16 inch from the tip, inside the barrel.

7. Solder thermistor lead wire to tip of needle. Use All-State No. 430 solder without flux. The solder should completely cover and seal the sharpened needle tip.

8. Solder long lead wire from thermistor to phono jack. Use rosin core solder. Test for continuity and shorts with ohmmeter.

9. Insert phono jack into sleeve and spot solder. Test again for continuity or shorts. This completes one thermistor probe. At least two are needed.

Construction of the heater probe is similar. The same gage but 1/2-inch longer needle should be used for this probe as was used for the thermistor probes. Nichrome wire, No. 26 AWG, is used for the heater resistance RH. This wire has to be coated with epoxy cement and the cement allowed to harden before assembly. This cement insulates the heater from the needle barrel. After the heater wire is prepared, assembly is again a series of steps. Reference to figure 8 will aid in understanding the steps.

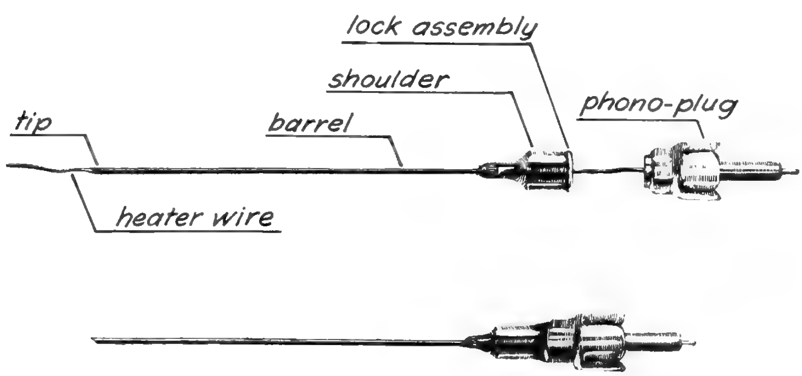

Figure 8. --Heater probe assembly, blown-up illustration with finished probe below.

Heater probe assembly steps.

1. Solder phono plug to lock assembly. Use rosin core solder.

2. Insert heater wire into needle barrel.

3. Silver-solder needle tip to heater wire.

4. Solder heater wire to tip of phono plug. Use All-State No. 430 solder.

5. Test heater probe by connecting it to a 6-volt battery for 1/2 second. The needle barrel should heat up along its entire length. This completes assembly of heater probe.

Two tips helpful in the construction of the thermistor probes and heater follow:

1. Use a heat sink, such as a hemostat[5] between thermistor and joint when soldering on lead wire extensions. Place all but the very tip of the needle in a vise when soldering the thermistor lead wire to the tip. Do not hold the soldering iron on the phono jack too long while spotting it to the copper sleeve--the plastic insulation inside the jack may become distorted so that a phono plug cannot be inserted in the jack.

2. Place the entire heat probe except the tip in a vise when silver-soldering the heater wire to the tip. This will prevent excessive heat from reaching the needle barrel and removing its temper.

Leads from the indicating meter housing to the sensing elements are No. 30 AWG stranded and shielded wire for the thermistor probes, and No. 16 AWG stranded wire for the heater probe. The probe end of these leads terminate in two phono plugs for connection to the thermistor probes, and one phono jack for connection to the heater probe. These leads can be made any length up to 50 feet. The meter-end of the leads terminates on a 4-prong Jones plug. A matching socket is mounted on the meter housing to accept this plug.

The accessories used with the instrument, with the exception of the drill jig, are readily available items. A one-fourth inch hand drill, drill bits the same diameter as the sensing elements, a stop watch, and a notebook are needed. The drill jigs must be manufactured by a machine shop with precision drilling equipment. These consist of a 2- by 1- by 1/4-inch thick block of hard steel. Figure 9 illustrates the jigs and hole spacings. The holes should be drilled with bits the same diameter as the sensing elements.

The purpose of these jigs is to maintain parallel spacing of the probes' holes to their extreme depth. This is important because the velocity readings are a function of the distance between the probes. Therefore, the distance between the holes on these drill jigs must be precise, and the holes must be drilled exactly perpendicular to the jig face.

Rectangular rings are attached to the edges of the drill jigs to which a strap can be attached as an aid in holding a jig against a stem while drilling holes for the probes.

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[5] A hemostat is a locking plier used to clamp blood vessels. It is available from surgical supply houses.

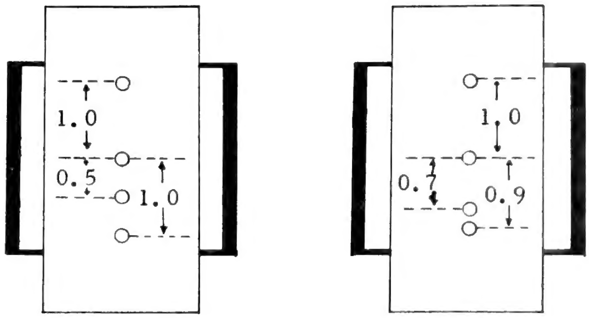

Figure 9. --Drill jigs used with sap-velocity meter. Not drawn to scale. Measurements shown are in centimeters.

OPERATING THE INSTRUMENT

As stated before, one man can easily carry and operate this instrument. Operation is a series of steps as outlined below:

1. Select stem or branch from which a velocity reading is desired.

2. Remove the rough part of the bark, if present, to obtain a flat surface. Place drill jig on this surface and strap to tree. The line of holes should be parallel to the direction of sap movement, with the longest spacing downstream.

3. Drill holes for the sensing elements. In summer space the holes 1.0 cm., 0 and 0.5 cm. In winter 1.0 cm., 0 and 0.9 cm. To test for presence or absence of movement, space the holes 1.0 cm., 0, and 1.0 cm. The proper depth for inserting the probes is assumed to be the midpoint of the conducting area. An increment core should reveal this depth. This increment core should be retained for later determination of density and moisture content (for use in determining sap flux).

4. Remove drill jig and insert sensing elements. The heater probe goes between the two thermistor probes. Select a pair of thermistor probes whose resistances are within 25 ohms of each other at room temperature (70°--80° F).

5. Connect lead wires from meter housing to probes.

6. Turn on meter by turning sensitivity control, R13, clockwise. Advance control until a reading is indicated on the readout meter. Adjust bridge balance control, R6, to balance as indicated by zero reading on the readout meter. Continue to advance sensitivity control, and to adjust bridge to balance until a position of the sensitivity control is reached that allows full-scale deflection for 10 units' change in the balance control.

7. Actuate heat-pulse switch, S2, for 1 second.

8. Actuate stopwatch immediately upon depressing the heat-pulse switch

9. Stop stopwatch when needle returns to zero.

10. Note the time elapsed (t_o) and record this time in seconds.

11. Use equation (5) to obtain heat-pulse velocity in cm/hour. Distances OA and OB were determined in step 3 above, t_o in step 10.

After completing the above sequence, subsequent velocity readings (steps 6 through 11) can be made at 30-minute intervals. (Thirty minutes between runs is necessary to allow all heat from the previous reading to dissipate.) If desired, remove the probes to a different location and repeat steps 1 through 11.

If comparison of movement is to be made between plants (same or different species) or over an extended time period (greater than a day or two), then sap flux must be used as the unit of comparison. Sap flux is determined with equation (9). The increment core obtained in step 3 is used to obtain wood bulk density and moisture content. If a simple determination of the variation in sap movement for a 24-hour period is desired, the heat-pulse velocity is sufficient, provided that all readings are taken in the same holes in the same plant.

LITERATURE CITED

Closs, R. L.
1958. The heat-pulse method for measuring sap flow in a plant. New Zeal. Jour. Sci. 1: 281-288.

Huber, B., and Schmidt, E.
1937. Eine Kompensations methods zur thermoelektrischen Messung langsamer Saftstrome. Ber. deutsch. Bot. Ges. 55: 514-529.

Marshall, D. C.
1958. Measurement of sap flow in conifers by heat transport. Plant Physiol. 33(6): 385-396.

Turner, Rufus P.
1960. Transistor circuits. Gernsback Libr. Inc. 160 pp., New York.

Vite, J. P., and Rudinsky, J. A.
1959. The water conducting systems in conifers and their importance to the distribution of trunk injected chemicals. Boyce Thompson Inst. Contrib. 20: 27-38.

Zarr, R.
1960. Sine-wave test generator. Electronics Experimenter's Handbook. 1960: 40.

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